PB90-134230

Regional Characterization of Air Quality and Deposition in the Coniferous Forests of the Western United States

NSI Technology Services Corp., Corvallis, OR

Prepared for:

Corvallis Environmental Research Lab., OR

1989

U.S. Department of Commerce
National Technical Information Service
NTIS

ERL-COR-1022D

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complet

1. REPORT NO. EPA/600/D-89/216	2.
3. PB90-134230	
4. TITLE AND SUBTITLE: A Regional Characterization of Air Quality and Deposition in the Coniferous Forest of the Western United States	5. REPORT DATE
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): Margi Bohm	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: NSI, ERL-Corvallis	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS: US Environmental Protection Agency, Environmental Research Laboratory, 200 SW 35th Street, Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED: Symposium Paper
	14. SPONSORING AGENCY CODE: EPA/600/2

15. SUPPLEMENTARY NOTES: In Proceedings of the APCA annual meeting, June 1989 in Anaheim, CA.

16. ABSTRACT

Regional patterns in air quality across the coniferous forests of the West are investigated using public data bases (NADP/NTN and AIRS). The results indicate that regional air pollution levels are low but that local airsheds can be highly polluted. Sulfur dioxide levels are generally less than 30 ppb, with maximum concentrations during the winter. High concentrations of sulfur dioxide have been measured in forests close to point sources. Ozone concentrations are usually less than 80 ppb, but often exceed the Federal Standard (hourly levels <120 ppb) in areas downwind of large urban and industrial centers during summer months. Acid deposition levels are 15-20% of those in the east, but cloudwater chemistry is more comparable, especially in southern California. Forest potentially threatened by current levels of air pollution are identified as being in the San Gabriel and San Bernardino Mountains, southern Sierra Nevada, central Utah, southern Arizona, Front Range of Colorado, and the western slopes of the Cascades in Washington.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT: Release to Public	19. SECURITY CLASS (This Report): Unclassified	21. NO. OF PAGES: 28
	20. SECURITY CLASS (This page): Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

EPA/600/D-89/216

89-135.1

A Regional Characterization of Air Quality and Deposition in the Coniferous Forests of the Western United States.

Margi Böhm
NSI Technology Services Corporation
U.S. EPA Environmental Research Laboratory
Western Conifers Research Cooperative
200 SW 35th Street
Corvallis, OR 97333

ABSTRACT.

Regional patterns in air quality across the coniferous forests of the West are investigated using public data bases (NADP/NTN and AIRS). The results indicate that regional air pollution levels are low but that local airsheds can be highly polluted. Sulfur dioxide levels are generally less than 30 ppb, with maximum concentrations during the winter. High concentrations of sulfur dioxide have been measured in forests close to point sources. Ozone concentrations are usually less than 80 ppb, but often exceed the Federal Standard (hourly levels < 120 ppb) in areas downwind of large urban and industrial centers during summer months. Acid deposition levels are 15 - 25% of those in the east, but cloudwater chemistry is more comparable, especially in southern California. Forests potentially threatened by current levels of air pollution are identified as being in the San Gabriel and San Bernardino Mountains, southern Sierra Nevada, central Utah, southern Arizona, Front Range of Colorado, and the western slopes of the Cascades in Washington.

INTRODUCTION.

Subsequent to their discovery and documentation in Scandinavia and north-eastern North America, acid deposition and gaseous pollution episodes have been reported at several locations in the western United States, i.e., the eleven states west of 105° W. Acid precipitation is widespread in California and has been documented in the Los Angeles Basin, San Francisco Bay, the San Joaquin Valley, and the Sierra Nevada.[1-3] Southern and Central California have received particular attention especially with respect to ozone[4], cloudwater concentrations[5-9], deposition loadings[10-12], and haze[13]. Observations of acidic precipitation and of sensitive high mountain watersheds showing signs of acidification have been noted in Colorado.[14-16] Reports describing air pollution in the Pacific Northwest[17,18] and the central and south-western states[13,19-24] are becoming more frequent.

This paper presents a characterization of emissions, ambient concentrations, and deposition of pollutants in the western United States with emphasis on areas covered by coniferous forests. The primary pollutants of concern are sulfur dioxide (SO_2) and nitrogen dioxide (NO_2); and the secondary pollutants discussed are ozone (O_3) and the concentration and deposition of acidic species in rain, snow, and cloudwater.

MATERIALS AND METHODS.

Emissions.

Estimates of emissions and the locations of point sources were obtained from the 1985 National Acid Precipitation Assessment Program (NAPAP) Interim Assessment and emissions database (1985 NAPAP National Emissions Data System, NEDS).[25] The emission data are estimates of the quantity of emission and the activity of the source during 1985.

Ambient Gas Concentrations.

Hourly concentrations of ambient sulfur dioxide, nitrogen dioxide and ozone are monitored at state level. Most of these data are available from the EPA Aerometric Information Retrieval System (AIRS). To limit uncertainties associated with non-standard calibration techniques prior to EPA standardization in 1979, the study period started on 01 January, 1980. Months with less than 500 sampling hours were excluded from the analysis.

Rain and Snow.

Weekly composite precipitation samples have been collected in the West since 1978 by the National Atmospheric Deposition Program/National Trends Network (NADP/NTN). The data were screened using the NADP/NTN flagging system to identify samples that were contaminated (bulk deposition or bird droppings), represented sampling periods longer than 8 days, were collected using non-standard sampling procedures, and for which there were no field or laboratory data. Confidence in the deposition loading estimates is not as high as that for the chemical concentrations because the quality of the precipitation amount data is not known. Consequently, actual loadings are usually under-estimated, especially when precipitation amounts are not available or sampler efficiency is low.[26] Although sample integrity can be compromised by using a weekly composite sampling period, and ionic concentrations may be under-estimated[27-29], it is felt that the concentration data are generally more accurate than the deposition data. Thus, deposition of ions across the West will not be discussed in as much detail as ionic concentration of precipitation.

Cloud.

Some information on cloud chemistry and frequency of occurrence in the West is available from the published literature, a summary of which is presented by Muir and Böhm[30]. There are no regional programs (such as the eastern Mountain Cloud Chemistry Project) studying cloud chemistry and deposition to western forests. In addition, there is little information on the frequency of occurrence and duration of cloud events in forested areas.

Site Selection.

A siting criterion of ≤ 20 km from the boundaries of coniferous forests was applied to select the sites used in this analysis. These sites were identified using 1:2,500,000 ecoregion maps.[31,32] Although ecoregions represent many different factors besides vegetation type, the areas identified as typically covered with coniferous forests correlate well with those depicted on the 1:3,168,000 Natural Vegetation Map[33] and 1:7,500,000 Major Forest Types Map[34]. A total of 24 sulfur dioxide, 20 nitrogen dioxide, 58 ozone, and 44 wet deposition sites were selected. To illustrate the most important spatial and temporal characteristics of air pollution regimes in and around western coniferous forests, the data from a subset of ten SO_2, nine O_3, and eleven NADP/NTN wet

deposition sites (choice based on geographic location, period of record, and data capture) will be discussed in this paper (Table I, Figure 1).

DATA ANALYSIS.

Ambient Gas Concentrations.

Monthly fractiles[35] (expressed as cumulative percent of total observed hours) are used to describe the occurrence of sulfur dioxide and ozone within 20 km of coniferous forests. Generally, sulfur dioxide concentrations are low and consequently no further analysis of the data was performed. Since ozone does occur at levels that may be detrimental to vegetation (hourly values > 60 ppb[36]), seasonal and spatial patterns in hourly ozone concentrations were further investigated using median and worst diurnal traces for each month. Worst day is defined as that with the highest maximum value following the hypothesis that peak ozone concentrations cause damage to vegetation.[37-39] Inter-annual variation is estimated from the number of hours/year ozone concentrations exceeded 80 ppb.

Nitrogen oxides are rapidly oxidized in the atmosphere and do not occur in concentrations high enough to negatively effect western forests. Secondary pollutants, such as peroxyacetyl nitrate (PAN) and aerosol nitrate may play a more important role in receptor areas far removed from NO_2 sources. Unfortunately there is a paucity of regional data on PAN and aerosol nitrate across the West and consequently the study of deposition of nitrogen to forest ecosystems is limited, in this paper, to that deposited during precipitation events.

Wet Deposition.

The weekly sampling period adopted by NADP/NTN prevents a detailed analysis of the frequency and duration of wet deposition as recommended by Hogsett et al.[35] The spatial patterns in precipitation chemistry are discussed using descriptive statistics for sulfate, nitrate, and hydrogen ion concentrations and deposition. The temporal patterns are approximated using weekly sulfate concentration data, to which a Fourier series (detrended with a class variable that addresses annual variations) is fitted using least squares regression. The curves presented have been tested for goodness of fit by week and year, and are superimposed on the weekly minimum, 25th percentile, 75th percentile and maximum values for the period of record.

RESULTS AND DISCUSSION.

Sulfur Dioxide.

Thresholds reported for direct foliar injury to plants from one hour exposures to SO_2, range between 500 and 2500 ppb for sensitive species.[40,41] Long-term thresholds have proven more difficult to estimate.[41] There is some evidence that annual average concentrations as low as 10-20 ppb, together with occasional peaks of 40-80 ppb can reduce tree growth.[42]

Emission Patterns.

Sulfur dioxide is emitted into the atmosphere during anthropogenic activities such as the combustion of fossil fuels, smelting of ores, manufacturing of steel, and refining of petroleum. Sulfur dioxide is also emitted naturally from sources such as fumaroles and volcanoes. Geothermal activity in North America is concentrated in Alaska, the western contiguous U.S., and Mexico and therefore natural sulfur dioxide emissions may play an important but sporadic role in the West.[25] For example, the Mount St. Helens eruptions between 1980 and 1982 contributed an estimated 0.34 million metric tons of SO_2 to the atmosphere, more than the annual contribution from man-made sources in the states of Washington and Oregon.

Anthropogenic sources of sulfur dioxide are scattered across the eleven western states, although major point sources are primarily located in Arizona, New Mexico, Colorado, Wyoming, Montana, and Washington (Figure 2). Total sulfur dioxide emissions by State for 1985 are estimated between 0.04 and 0.59 million metric tons/year.[25] Interestingly, California has the second highest estimated emissions despite the absence of sources emitting more than 500 metric tons SO_2/year (Figure 2).

In 1985, the estimated total SO_2 emissions for the West were 2.15 million tons, 10% of the national estimate.[25] With the exception of Arizona, the western states generally have SO_2 emission densities less than 1.50 metric tons/km^2, [43] although orographic/meteorological conditions in many of the source areas may prevent dispersion of plumes, and localized pockets of high ambient SO_2 levels probably exist.

Regional trends in sulfur dioxide emissions imply that the Western situation has not changed much during the last decade.[25] These results do not reflect the situation at a state level. SO_2 emissions increased between 1980-1986 by an estimated 25% in Idaho and by 10.5% in Wyoming, remained unchanged in Oregon and Colorado, and decreased slightly elsewhere.[25]

SO_2 emissions in the West are expected to stabilize at between 2.0 - 2.2 million tons/year by 1990.[44,45] After 1990, increasing emissions from stationary fuel combustion sources should outweigh the continuing decline in smelter emissions, resulting in a gradual increase in SO_2 emissions by the year 2000. These projections are approximate since emissions from several large smelters in northwestern Mexico are expected to increase through the 1990s and may influence SO_2 levels in Arizona and New Mexico.[45]

Ambient Concentrations.

Data from ten of the twenty-four SO_2 sites identified within 20 km of coniferous forests are discussed (Table I). The period of operation of these sites is important, especially in areas where large SO_2 sources have since been shut down. The following discussion serves to identify potential exposure conditions in and around certain coniferous forests by providing an overview of the levels of ambient sulfur dioxide concentrations ($[SO_2]$) that have recently been experienced in the West. An analysis of point source close-downs and the influence on $[SO_2]$ is not included in the scope of this paper.

The lowest ambient $[SO_2]$ were measured at Apache Sitgreaves NP, AZ (1982-1986); San Bernardino, CA (1980-1981, 1983-1984); and Albuquerque, NM (1980-1986) where levels greater than 10 ppb were rarely encountered (Figure 3). Concentrations at Olympic NP, WA (1980-1986) are also generally low; $[SO_2] > 30$ ppb occurred during less than 5% of measured hours/month. On the other hand, Greenlee County, AZ (1980-1984); Shoshone County, ID (1980-1983); Kellogg, ID (1980-1981); and Anaconda Deer Lodge, MT (1981) were often exposed to high $[SO_2]$. At Greenlee County, the seasonal maxima occur during winter (Nov - Jan) when SO_2 concentrations exceeded 80 ppb during 20% of the measured hours/month; summer-time exposures were also frequent ($[SO_2] > 80$ ppb during 10% of measured hours/month). Anaconda Deer Lodge was exposed to $[SO_2] > 80$ ppb during at least 15% of measured hours during the winter and early summer months, whereas Kellogg showed a summer maximum of 17% of measured hours/month (Aug-Oct), and spring-time sub-maximum with $[SO_2] > 80$ ppb during 10% of measured hours/month.

The remaining sites were usually exposed to $[SO_2] < 40$ ppb. Denver, CO (1980-1986); King County, WA (1980-1986); Burbank, CA (1980-1986); and Bountiful, UT (1980-1986) recorded more frequent occurrences of the higher concentrations during winter. At Bellingham, WA (1983-1986) and Miami, AZ (1980-1986), $[SO_2]$ were less than 30 ppb with a small maximum in summer.

A comparison between ambient $[SO_2]$ and the locations of point sources illustrates the local nature of this pollutant. Sites reasonably close to sulfur dioxide sources with emissions greater than 100 metric tons/year (Bellingham and King County, WA; Burbank, CA; Denver, CO; Bountiful, UT; and Miami, AZ) recorded ambient $[SO_2] > 20$ ppb during all the months of the year. On the other hand San Bernardino, CA; Apache Sitgreaves NP, AZ; and Albuquerque, NM are also located near to sources, however, high ambient $[SO_2]$ were rarely measured.

Nitrogen Dioxide (NO_2).

NO_2 does not occur in concentrations high enough to be phytotoxic to vegetation. However, as NO_2 is a precursor of ozone, it is appropriate to discuss the emission patterns of this pollutant.

Emission Patterns.

Transportation (primarily highway vehicles) is the major source of anthropogenic nitrogen oxides (NO_x) in the West.[44] Consequently, large emissions occur in and around cities, with fewer sources in rural and remote areas, except around large point sources.

The 11 western states emitted an estimated 3.01 million metric tons of NO_x in 1985, 15.8% of the national total.[25] The highest emissions (estimated at 1.11 million metric tons/1985) were for California (second only to Texas on a national scale), with Oregon and Idaho (0.21 and 0.08 million metric tons/1985 resp.) having the lowest emissions in the West.[25] The largest emission densities are found in and around the major cities such as Los Angeles, San Francisco, Puget Sound (Seattle-Tacoma), Salt Lake City, Las Vegas, Phoenix, Albuquerque, and Denver.[43]

Regionally, NO_x emissions in the West decreased slightly between 1980 and 1985.[25] At state level, Arizona, Colorado, and Wyoming show larger estimates for 1985 than for 1980 (increased power plant emissions) as did Montana and Nevada (increased emissions from power plants and highway vehicles), whereas California, Oregon, and Washington show decreases. Nitrogen oxide emissions are expected to remain constant through the 1980s as further controls are placed on mobile sources; but after 1990, a gradual increase in emissions is projected.[45]

Ozone.

Ozone is a secondary pollutant created in the presence of nitrogen oxides, volatile organic compounds (hydrocarbons) and sunlight. The major source areas for ozone are therefore related to those for NO_x and hydrocarbons. Since ultra-violet light energy is required to drive the photochemical reactions, ozone concentrations fluctuate both seasonally and with latitude.

Ozone is the only regionally dispersed pollutant known to injure foliage and cause tree mortality.[46] Adverse effects can start occurring at concentrations above 60 ppb[36], however, effects generally manifest themselves during short exposures to concentrations greater than 80 ppb[37].

Ambient Concentrations.

Data from nine of the fifty-eight O_3 sites identified within 20 km of coniferous forests are presented (Table I). The following discussion serves to identify potential exposure conditions in and around certain coniferous forests by providing an overview of the levels of ambient ozone concentrations that have recently been experienced in the West.

The lowest hourly ozone concentrations were recorded at Olympic NP, WA, where levels never exceeded 60 ppb (Figure 4). Sites such as South Lake Tahoe, CA, Mammoth Lakes, CA, Apache Sitgreaves NP, AZ, and Albuquerque, NM were exposed to $60 < [O_3] < 80$ ppb during the summer months (Figure 4). Exposure to ozone at Albuquerque occurred in summer (Apr-Sep), when such concentrations were measured during 2-10% of measured hours/month. $[O_3]$ increased between Mar-Aug at Apache Sitgreaves NP, with 5-25% of measured hours measuring values

between 60 and 80 ppb. The ozone season in the Sierra Nevada extended from Mar-Nov, with concentrations between 60 and 80 ppb measured 2-25% of measured hours/month at South Lake Tahoe, and 2-30% of measured hours/month at Mammoth Lakes.

Hourly $[O_3]$ > 100 ppb were measured at King County, WA, Boulder, CO, Bountiful, UT, and Lake Gregory, CA (Figure 4). Concentrations in this range were recorded during mid-summer (Jun-Aug) for 5% of measured hours/month, except at Lake Gregory. The San Bernardino Mountains are exposed to hourly ozone concentrations in excess of 100 ppb all year round, with frequencies of occurrence of 1-2% of measured hours in winter and 10% in summer.

Most of the sites show increased ozone levels in summer, with maximum exposure during June, July, and August. The exceptions are Olympic NP where hourly concentrations never exceeded 60 ppb, and the sites in Arizona (Flagstaff and Apache Sitgreaves NP) where higher concentrations occurred during May. Boulder, CO; Bountiful, UT; Lake Gregory, Mammoth Lakes, and South Lake Tahoe, CA recorded elevated ozone concentrations (> 80 ppb) at least once a month. Of these, Bountiful and Lake Gregory were exposed to hourly $[O_3]$ > 120 ppb during at least 6 of the 12 months.

Seasonal and diurnal trends in $[O_3]$ were further investigated using monthly median and worst diurnal patterns for Lake Gregory, Mammoth Lakes, and South Lake Tahoe, CA, and King County, WA. The magnitude of elevated $[O_3]$ at Lake Gregory is remarkable and serves to illustrate the consequences of urbanization in a poorly ventilated valley (Figures 5 and 6). Ozone concentrations peak late in the afternoon at Lake Gregory, implying long range transport (Figure 5). Mammoth Lakes and South Lake Tahoe show less diurnal variation than Lake Gregory and King County, as expected for remote, high elevation sites[47] (Figure 5). King County exhibits a diurnal pattern characteristic of an urban site with $[O_3]$ reaching the minimum detection limit of the monitoring instrument (5-10 ppb) during the night and early morning hours (Figure 5).

Ozone concentrations at Lake Gregory have a distinct seasonal pattern, with marked increases during the summer (Figure 5). The Sierra Nevada sites show very little seasonality in $[O_3]$, although winter concentrations are lower than those in summer (Figure 5). The seasonal pattern in ozone at King County does not exhibit marked changes in concentration, but rather in diurnal cycle, with ozone formation occurring earlier in summer than winter (Figure 5). These seasonal patterns illustrate the influence of solar energy in the presence of an abundant (Los Angeles Basin) and limited (King County) supply of ozone precursors.

The median monthly diurnal patterns of $[O_3]$ measured at Mammoth Lakes and South Lake Tahoe do not show depletion of ozone during the night and early morning hours, as would be expected for sites measuring locally generated ozone (e.g., compare the graphs with that for King County in Figure 5). Thus, although the urban centers of Mammoth Lakes and South Lake Tahoe probably generate many of the ozone precursors, there is evidence to suggest that either additional ozone is being transported to these areas, or the background levels are of the order of 30-40 ppb. Similar results have been documented in Alberta, Canada.[47]

The worst ozone days on record, again, illustrate the extreme situation in the San Bernardino Mountains (Figure 6). The worst days are similar at Mammoth Lakes, South Lake Tahoe, and King County, although the latter sites are exposed to longer periods of elevated levels than King County.

The number of hours/year that $[O_3] > 80$ ppb do not vary much from year to year at Lake Gregory, South Lake Tahoe, or King County (Table II). Furthermore, any trend is not consistent across the three sites and, therefore, it is suspected that any interannual variation in $[O_3]$ is a function of erratic climatic conditions. Similar results have been found in southern California.[48]

Acid Precipitation.

The chemical species responsible for depressing the pH of rain-water are secondary pollutants, derived primarily from the oxidation of sulfur and nitrogen oxides. The rate of oxidation and the transport of the primary and secondary pollutants determines the areas where acid deposition is most likely to occur. Eleven NADP/NTN sites within 20 km of coniferous forests and with six years or more of data are used to illustrate the spatial and temporal patterns of acid precipitation across the western United States.

Precipitation Chemistry - Concentration.

The ionic compositions of precipitation in the West are generally 15 - 25% of eastern values. Mean weekly concentrations of sulfate range between 5.11-26.17 μmol/l, 2.52-66.11 μmol/l for nitrate, and 3.56-33.19 μmol/l for hydrogen ions; and the 75th percentile for sulfate concentrations ranges between 6-24 μmol/l, 3-60 μmol/l for nitrate, and 4-24 μmol/l for hydrogen ions (Table IIIa). Extreme concentrations such as 350 μmol/l sulfate, 917 μmol/l nitrate, and 645 μmol/l of hydrogen ions have been recorded in a forested site north of Los Angeles (Table IIIa). Extreme values of these orders of magnitude are infrequent, site specific, and usually associated with small precipitation amounts, but should not be ignored since chemical inputs at such high levels may be toxic to forest ecosystems.

The chemical composition of precipitation across the West exhibits a spatial pattern related, not surprisingly, to the proximity of the site to pollution sources (Table IIIa, Figures 1,2). Sites removed from anthropogenic sulfur emission sources (e.g., Hoh River, WA; H.J. Andrews Forest, OR; Yosemite NP, CA; Headquarters, ID; Glacier NP, MT) have lower mean and peak sulfate concentrations (weekly mean 5-7 μmol/l) than sites in close proximity or downwind of paper/pulp mills (e.g., Alsea Forest, OR, 8.6 μmol/l) and fossil fuel refineries and power plants (e.g., San Gabriel Mountains - Tanbark Flat, CA, 26 μmol/l; and the Front Range, CO where weekly mean $[SO_4^{2-}]$ ranges between 15-20 μmol/l).

The relationship between nitrate concentrations and proximity to urban/industrial complexes is even more pronounced (Table IIIa, Figures 1,2). Hoh River and Alsea Forest have very low nitrate concentrations (2.5 and 4 μmol/l resp.); slightly higher values (6-9 μmol/l) are recorded at H.J. Andrews Forest, Headquarters, and Glacier National Park which are located near reasonably

large cities; and much higher concentrations (weekly mean [NO_3^-] between 16-66 μmol/l) are found at sites downwind of large urban complexes such as Central California Valley (Yosemite and Sequoia NP), Los Angeles Basin (Tanbark Flat), and the Front Range (Manitou, CO; Alamosa, CO; and Bandelier NM, NM).

The spatial pattern in acidity (hydrogen ion concentration) is similar to that for sulfate and nitrate. Although the northern sites exhibit similar mean hydrogen ion concentrations (weekly mean [H^+] around 3-5 μmol/l), Alsea Forest, Yosemite NP and Sequoia NP, and Headquarters have recorded peak acidities [H^+] > 60 μmol/l, twice that at the other northern sites. On average, the Front range receives precipitation with twice the acidity (mean [H^+] ~ 10 μmol/l) as the northern sites; and although the peak values are of the same order of magnitude, the Front range sites are more often exposed to elevated acidities (as illustrated by a difference of 2 in the 75th percentiles in Table IIIa). The precipitation sampled close to a large urban area (Tanbark Flat 35 km north of downtown Los Angeles, CA), is 3-6 times more acidic than that recorded at other NADP/NTN sites in the West.

Seasonal patterns in precipitation chemistry across the West are illustrated using [SO_4^{2-}] (Figure 7). There is a general increase in sulfate concentrations during the summer (possibly related to lower volume events) and a decrease during winter, although at more remote sites, this pattern is not easily discernable. The range in concentration is generally lower during winter than during summer, possibly related to seasonal patterns in occurrence, form (snow versus rain), and origin of air masses. Similar results have been noted at Sequoia NP, CA[12], and in Colorado[14,15].

Precipitation Chemistry - Deposition.

Annual wet-deposition estimates for sulfate, nitrate, and hydrogen ions are generally 15-25% of eastern values (e.g., in 1986[26], deposition estimates across the West were SO_4^{2-} : 2-9 kg/Ha; NO_3^- : 1-5 kg/Ha; and H^+ : 0.03-0.1 kg/Ha). Deposition of nitrate follows similar spatial patterns to concentration (Table IIIb), with areas in close proximity to urban/industrial centers recording higher loadings. Patterns in sulfate deposition are more complex, possibly a consequence of the marine influence at remote sites such as Hoh River, Alsea Forest, and H.J. Andrews Forest in conjunction with the high precipitation amounts recorded in these areas.

Temporal patterns in deposition are related to seasonal patterns in precipitation. In general, most deposition to forested areas in the West occurs during the winter in the form of snow.

Elevational Effects

High elevation ecosystems are considered sensitive to anthropogenically modified precipitation chemistry.[49] A preliminary analysis of weekly composite sulfate concentrations for 12 NADP/NTN sites in six study areas in the Colorado and Wyoming Rockies, showed that [SO_4^{2-}] in snow were consistently lower than those in rain; snow samples collected at lower elevations contained greater concentrations of sulfate relative to higher elevations, regardless of concentration; and a similar relationship for rain was not well established.[50] Contrary to these results for weekly composite

samples, increases in the acidity of precipitation events with elevation have been noted in New Mexico[51] and Scotland[52].

Unfortunately, such results cannot be generalized and assumed to be the case in other areas. Elevational gradients are affected by a complex interaction of orographic features, mesoscale and local meteorology, distance from upwind pollution sources, as well as the seasonal variations in precipitation form, pollution emissions and meteorology. Further research is required to identify the relationships between acid deposition and elevation.

Cloud

A recent survey of the published literature on cloud chemistry and frequency of occurrence in the West has been presented by Muir and Böhm.[30] A precis of their results is presented.

Interception of non-precipitating (stratus and stratocumulus) clouds across the West is greatest along the Pacific coast, in the Coast Range of northern California, Oregon and Washington and along the western slopes of the Cascades. Interception is more frequent in summer in the south and winter in the north. The frequency of occurrence of stratus and stratocumulus clouds is low over the Sierra Nevada and central Western Mountains, although total cloud interception is probably underestimated due to a lack of information on the frequency of occurrence of cap clouds. Cloud interception is also considered low along the eastern slopes of Wyoming, Colorado, and New Mexico.

Western cloud events exhibit a large range of concentrations, e.g., $[NO_3^+]$ ~ 16,000 μmol/l and $[SO_4^{2-}]$ ~ 4,500 μmol/l have been recorded. Samples from southern California are generally more acidic than those from the more northern sites (mean minimum pHs = 2.52 and 4.48, respectively). Southern California samples tend to be dominated by SO_4^{2-}, NO_3^-, and NH_4^+, while samples from Alaska, Oregon, and northern California are mainly influenced by sea-salt and marine constituents (Na^+, Cl^-, and SO_4^{2-}). Concentrations of all ions in western cloudwater are positively correlated, but correlations are strongest between ions that result primarily from one of three source groups; sea salt, soil dust, and anthropogenic sources of sulfur and nitrogen.

CONCLUSIONS.

Although estimated total SO_2 emissions in the West are 10% of the national estimate, pockets of high ambient $[SO_2]$ were found. For example, forests near Greenlee, AZ, Kellogg and Shoshone, ID, and Anaconda Deer Lodge, MT were frequently exposed to $[SO_2]$ > 80 ppb during the early 1980s. Indeed, SO_2 induced damage has been recorded in Montana.[53] A detailed study of the air pollution meteorology of the areas around the major SO_2 sources is required to estimate the total forest area potentially impacted by sulfur dioxide in the West.

Nitrogen dioxide is not likely to cause damage to terrestrial ecosystems at current levels. However, since NO_x is a precursor of ozone, PAN, and nitrates, the magnitudes of emissions close to forests

(such as southern and central California, the Front Range of Colorado, and the Cascades of Washington) are of concern, especially since emissions are projected to gradually increase.

Ozone levels in and near forested areas are greatest downwind of large urban and industrial centers. Ponderosa and Jeffreys Pine forests surrounding the Los Angeles Basin exhibit foliar damage directly related to ozone[4] and evidence of growth reduction in Jeffreys Pine has been recorded in the southern Sierra Nevada[54,55]. Comparisons of the fractiles and diurnal patterns of ozone in these areas with those for other sites across the West, indicate that ozone levels in and near the forests of Utah and Arizona, the northern Front Range, and the western slopes of the northern Cascades are probably impacted by similar levels of ozone (although for shorter periods of time) to the western slopes of the central Sierra Nevada, and these levels may be debilitating to local forest species. More ozone data in forested areas are required to accurately assess the potential for ozone damage in areas besides southern California.

In general, concentrations and deposition of sulfate, nitrate, and hydrogen ions during precipitation events, are about 15 - 25% of eastern values, although extreme events can occur. Urban and industrial areas seem to elevate concentrations of sulfate and nitrate by a factor of 2 - 6. Temporal patterns show highest concentrations during the spring, summer, and fall.

It is uncertain if acid precipitation increases or decreases with elevation. Since many high elevation areas across the West have shallow, poorly buffered soils[49] and lakes with low alkalinity values[3], more information on the relationship between elevation and acid precipitation in western forests is required.

The available data on cloud chemistry indicate that the regions of the western United States in which cloud interception is greatest, generally have low ionic strengths. Even though cloud interception is low in southern California, the chemistry of the few events sampled is so concentrated that adverse effects to terrestrial ecosystems may occur. Similarly, total deposition of ionic species intercepted by the foliage and introduced to soil systems at the northern sites may not be inconsequential.

Generally, it is concluded that regional air pollution levels are low across the West but that local airsheds can be highly polluted. The forests most susceptible to atmospheric stresses are those downwind of major urban and industrial complexes. Forests potentially threatened by current levels of air pollution are identified as being in the San Gabriel and San Bernardino Mountains, southern Sierra Nevada, Central Utah and Arizona, the Front Range of Colorado, and the western slopes of the Cascades in Washington.

Finally, it is concluded that the paucity of regional data describing air quality, meteorology, and physiological characteristics of western forests makes it impossible to regionally describe the impact of man on air quality and deposition in and around the coniferous forests of the West.

ACKNOWLEDGEMENTS

I would like to acknowledge Terralyn Vandetta for her invaluable programming skills and my reviewers for their helpful comments and suggestions. The SO_2 and O_3 fractile data were provided by Al Lefohn, A.S.& L. Associates, Helena, Montana. This research was supported by funds provided by the Western Conifers Research Cooperative within the joint U.S. Environmental Protection Agency - USDA Forest Service Forest Response Program. The Forest Response Program is part of the National Acid Precipitation Assessment Program.

REFERENCES

1. D.R. Lawson and J.G. Wendt, "Acid deposition in California, SAE Technical Paper 821246 (1982).

2. J.G. McColl, "A survey of acid precipitation in Northern California (Final Report)", CARB, Sacramento, CA, Contract A7-149-30 (1980).

3. J.M. Melack, J.L. Stoddard and C.A. Ochs, "Major ion chemistry and sensitivity to acid precipitation of Sierra Nevada Lakes", Water Resources Research, 21:27 (1985).

4. P.R. Miller, O.C. Taylor, and M.P. Poe, "Spatial variation of summer ozone concentrations in the San Bernardino Mountains", Presented at the 79th Annual APCA Meeting, Minneapolis, Minnesota, June 1986.

5. J.M. Waldman, J.W. Munger, D.J. Jacob, R.C. Flagan, J.J. Morgan, and M.R. Hoffmann, "Chemical composition of acid fog", Science, 218:677 (1982).

6. R.L. Brewer, E.C. Ellis, R.J. Gordon, and L.S. Shepard, "Chemistry of mist and fog from the Los Angeles urban area", Atmospheric Environment, 17:2267 (1983).

7. J.W. Munger, D.J. Jacob, J.M. Waldman, and M.R. Hoffmann, "Fogwater chemistry in an urban atmosphere", Journal of Geophysical Research, 88(C9):5109 (1983).

8. D.J. Jacob, J.M. Waldman, J.W. Munger, and M.R. Hoffmann, "Chemical composition of fogwater along the California coast", Environment, Science, and Technology, 19:730 (1985).

9. J.M. Waldman, J.W. Munger, D.J. Jacob, and M.R. Hoffmann, "Chemical characterization of stratus cloudwater and its role as a vector for pollutant deposition in a Los Angeles pine forest", Tellus, 37B:91 (1984).

10. R.L. Leonard and C.R. Goldman, "Some measurements of the pH and chemistry at Davis and Lake Tahoe, California", Water, Air, and Soil Pollution, 15:153 (1981).

11. H.M. Liljestrand and J.J. Morgan, "Spatial variations of acid precipitation in southern California", Environ. Sci. Techn., 15(3):333 (1981).

12. T.J. Stohlgren and D.J. Parsons, "Variation of wet deposition chemistry in Sequoia National Park, California", Atmospheric Environment, 21(6):1369 (1987).

13. E.S. Macias and J.O. Zwicker, "Regional haze case studies in the southwestern US- I. Aerosol chemistry composition", Atmospheric Environment, 15(10/11):1971 (1981).

14. C.T. Nagamoto, F. Parungo, R. Reinking, R. Pueschel, and T. Gerish, "Acid clouds and precipitation in eastern Colorado", Atmospheric Environment, 17(6):1073 (1983).

15. J. Harte, G.P. Lockett, R.A. Schneider, H. Micheals, and C. Blanchard, "Acid precipitation and surface water vulnerability on the western slope of the High Colorado Rockies", Water, Air, and Soil Pollution, 25:313 (1985).

16. M.J. Reddy, T.D. Liebermann, J.C. Jelinski, and N. Caine, "Variation in pH during summer storms near the continental divide in central Colorado, USA", Arctic and Alpine Research, 17(1):79 (1985).

17. G.A. McBean and S. Nikleva, 1986: "Composition of snow in Pacific coastal mountains", Atmospheric Environment, 20(6):1161 (1986).

18. R.L. Edmonds and F.A. Basabe, "Ozone concentrations in Douglas-fir forests in western Washington", Submitted to Canadian Journal of Forest Research (1988).

19. G.A. Dawson, "Ionic composition of rain during sixteen convective showers", Atmospheric Environment, 12:1991 (1978).

20. R.G. Flocchini, T.A. Cahill, L.L. Ashbaugh, and R.A. Eldred, "Seasonal behavior of particulate matter at three rural Utah sites", Atmospheric Environment, 15:315 (1981).

21. R.G. Flocchini, T.A. Cahill, M.L. Pitchford, R.A. Eldred, P.J. Feeney, and L.L. Ashbaugh, "Characterization of particles in the arid west", Atmospheric Environment, 15(10/11):2017 (1981).

22. W.P. Linak and T.W. Peterson, "Visibility-pollutant relationships in southern Arizona - II. A winter/summer field study", Atmospheric Environment, 17(9):1811 (1983).

23. J.J. Messer, "Geochemically alkaline snowpack in northern Utah mountains in spring of 1982", Atmospheric Environment, 17(5):1051 (1983).

24. E. Thomas and P.R. Buseck, "Characterization of a rural aerosol from eastern Arizona", Atmospheric Environment, 17(11):2299 (1983).

25. M. Placet and D.G. Streets, "NAPAP Interim Assessment, The causes and effects of acid precipitation, Volume II. Emissions and Control", NAPAP Headquarters, Washington DC, 1987.

26. National Atmospheric Deposition Program, "NADP/NTN Annual Data Summary: Precipitation chemistry in the United States, 1986", Available from Program coordinator, NADP/NTN Coordination Office, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO. 80523, 1987.

27. R.G. De Pena, K.C. Walker, L. Lebowitz, and J.G. Micka, "Wet deposition monitoring - effect of sampling period", Atmospheric Environment, 19(1):151 (1985).

28. J.N. Galloway and G.E. Likens, "Calibration of collection procedures for the determination of precipitation chemistry", Water, Air, Soil Pollution, 6(2/3):241 (1976).

29. J.N. Galloway and G.E. Likens, "The collection of precipitation for chemical analysis", Tellus, 30:72 (1978).

30. P.S. Muir and M. Böhm, "Cloud chemistry in the western United States: A synopsis of current information", Presented at 82nd Annual APCA Meeting, Anaheim, CA, June 1989.

31. J.M. Omernik and A.L. Gallant (1986): Maps "Ecoregions of the Conterminous United States, 1:2,500,000", Published by U.S. Government Printing Office, Digitized information available from A. Herstrom, Northrop Services Inc., Corvallis, Oregon, 97333 (1986).

32. J.M. Omernik, "Ecoregions of the Conterminous United States", Annals of the Association of American Geographers, 77(1):118 (1987).

33. A.W. Kuchler, "Potential Natural Vegetation of the Conterminous United States, 1:3,168,000", Published by the American Geographical Society (Special Publication # 36), Broadway, 156th Street, New York, NY, 100032, Lithographed by A. Hoen & Co., Inc., Baltimore, Maryland (1975).

34. National Atlas of the United States of America, US Dept of the Interior, Geological Survey, Map "Major Forest Types, 1:7,500,00", Compiled from information from the US Forest Service, pp. 154 (1967).

35. W.E. Hogsett, D. Olszyk, D.P. Ormrod, G.E. Taylor, and D.T. Tingey, "Air pollution exposure systems and experimental protocols: Volume 1: A review and evaluation of performance", EPA 600/3-87/037a, Environmental Research Laboratory, Office of Research and Development, Corvallis, OR 97333, September, 1987.

36. E.J. Pell, "The impact of ozone on the bioenergetics of plant systems", In: Air Pollution Effects on Plant Growth, M. Dugger, ed., Washington, D. C., American Chemical Society, ASC Symposium Series, 3:106 (1974).

37. O.C. Taylor ed., "Oxidant Air Pollution Effects on a Western Coniferous Forest Ecosystem", Task B Report, University of California Air Pollution Research Center, Riverside, CA (1973).

38. A.S. Lefohn, "A comparison of ambient ozone exposures for selected nonurban sites", In: Proceedings of the 77th Annual APCA Meeting, San Francisco, June, 1984.

39. A.S. Lefohn and C.K. Jones, "The characterizing of ozone and sulfur dioxide air quality data for assessing possible vegetation effects", JAPCA, 36(10):1123 (1986).

40. W.W. Heck and C.S. Brandt, "Effects on vegetation: Native, crops, forests", Chapter 4 in A.C. Stern (ed.), Air Pollution, Third Edition, Academic Press, New York, 1977.

41. S.B. McLaughlin, "SO_2, vegetation effects and the air quality standard: Limits of interpretation and application", A Speciality Conference on the Proposed SO_x and Particulate Standard, Atlanta, GA (APCA) 1981.

42. F. Last and P. Rennie, "Forest changes expert meeting no. 3", Stockholm Conference on Acidification of the Environment, June 20-30, 1982 (Swedish Ministry of the Environment) 1982.

43. L.R. Chinkin, D.A. Latimer, and L.A. Mahoney, "Western States Acid Deposition Project, Volume 2: A review of emission inventories needed to regulate acid deposition in the western United States", Final Report SYSAPP-87/072, Western Governors' Association, Denver, CO, 148 pp (1987).

44. G.M. Hidy and J.R. Young, "Acid deposition and the west, a scientific assessment", ERT Document No. P-D572-503, March 1986.

45. J.R. Young, E.C. Ellis, and G.M. Hidy, "Deposition of air-borne acidifiers in the western environment", Journal of Environmental Quality, 17(1):1 (1988).

46. J.N. Woodman, "Pollution induced injury to North American forests: Facts and suspicions", Tree Physiology, 3:1 (1987).

47. A.H. Legge, "The present and potential effects of acidic and acidifying air pollutants on Alberta's environment. Critical Point I, 1988", Prep. for the Acid Deposition Research Program by the Kananaskis Centre for Environmental Research, The University of Calgary, Calgary, Alberta, ADRP-B-16-88, ISBN 0-921625-23-5, 75p. (1988).

48. H.M. Walker, "Ten-year ozone trends in California and Texas", JAPCA, 35(9):903 (1985).

49. M.T El-Ashry, "Study shows mountain ecosystems may be especially sensitive to acid deposition", Ambio, 14131:174 (1985).

50. W.G. Warren, M. Böhm, and D. Link, "Statistical methodology for exploring elevational differences in precipitation chemistry", Presented at 82nd Annual APCA Meeting, Anaheim, June, 1989.

51. C.J. Popp, A. Long, "Acidic effects in Western North America - Trends, sources, and altitude effects in New Mexico, 1979-1985", Water, Air, and Soil Pollution, 30:125 (1986).

52. D. Fowler, J.N. Cape, I.D. Leith, T.W. Choularton, M.J. Gay, and A. Jones, "The influence of altitude on rainfall composition at Great Dun Fell", Atmospheric Environment, 22(7):1355 (1988).

53. C.E. Carlson, "Sulfur damage to Douglas-fir near a pulp and paper mill in western Montana", Report 74-13, USDA-USFS Northern Region, Missoula, Montana (1974).

54. D.L. Peterson, M.J. Arbaugh, V.A. Wakefield, and P.R. Miller, "Evidence of growth reduction in ozone-injured Jeffrey pine (Pinus jeffrey Grev. and Balf.) in Sequoia and Kings Canyon National Parks", JAPCA, 37:906 (1987).

55. D.L. Peterson and M.J. Arbaugh, "An evaluation of the effects of ozone injury on radial growth of Ponderosa pine (Pinus ponderosa) in the southern Sierra Nevada", JAPCA, 38(7):921 (1988).

Table I. Descriptions of pollutants measured and period of record by site. (Site numbers refer to Figure 1, NP - National Park, and NM - National Monument.)

Site #	Name	State	Pollutant (per. record)
1	Bellingham	WA	SO_2 (83-86)
2	Olympic NP	WA	SO_2 (80-86); O_3 (82-86)
3	Hoh River	WA	Precipitation (80-87)
4	King County	WA	SO_2 (80-86); O_3 (80-86)
5	Alsea Forest	OR	Precipitation (79-87)
6	H.J. Andrews Forest	OR	Precipitation (80-87)
7	South Lake Tahoe	CA	O_3 (81,84-86)
8	Yosemite NP	CA	Precipitation (81-87)
9	Mammoth Lakes	CA	O_3 (84-86)
10	Sequoia NP	CA	Precipitation (80-87)
11	Santa Barbara County	CA	O_3 (80-86)
12	Tanbark Flat	CA	Precipitation (82-87)
13	Burbank	CA	SO_2 (80-86)
14	Lake Gregory	CA	O_3 (80-86)
15	San Bernardino County	CA	SO_2 (80-81,83-84)
16	Shoshone County	ID	SO_2 (80-83)
17	Kellogg	ID	SO_2 (80-81)
18	Headquarters	ID	Precipitation (82-87)
19	Glacier NP	MT	Precipitation (80-87)
20	Anaconda Deer Lodge	MT	SO_2 (80)
21	Bountiful	UT	SO_2 (80-86); O_3 (80-86)
22	Boulder	CO	O_3 (81-86)
23	Denver	CO	SO_2 (80-86)
24	Manitou	CO	Precipitation (78-87)
25	Alamosa	CO	Precipitation (80-87)
26	Bandelier NM	NM	Precipitation (82-87)
27	Albuquerque	NM	SO_2 (80-86)
28	Flagstaff	AZ	O_3 (81-85)
29	Apache Sitgreaves NP	AZ	SO_2 (82-86); O_3 (80-83)
30	Miami	AZ	SO_2 (80-86)
31	Greenlee County	AZ	SO_2 (80-84)

Table II. Number of hours/year (percent) that hourly [O_3] > 80 ppb at Lake Gregory, South Lake Tahoe, and King County. Site number refers to Figure 1.

#	Site Name	Year							
		80	81	82	83	84	85	86	87
14	Lake Gregory	19.1	21.6	20.2	19.0	21.4	20.1	20.0	13.6
7	S. Lake Tahoe	0.5	0.6	0.1	0.0	0.1	0.2	0.3	0.6
4	King County	0.1	0.9	0.2	0.3	0.1	0.5	0.8	0.5

Table IIIa. Minimum, 25th percentile, arithmetic mean, 75th percentile, and maximum weekly concentration statistics for sulfate, nitrate, and hydrogen ions (μmol/l) in precipitation. Site numbers refer to Figure 1.

		Sulfate						Nitrate						Hydrogen Ion					
#	Site Name	N	Min	25th	Mean	75th	Max	N	Min	25th	Mean	75th	Max	N	Min	25th	Mean	75th	Max
3	Hoh River	273	0.16	2.39	5.60	6.14	66.42	273	0.16	0.65	2.52	2.26	83.88	281	0.08	2.24	4.07	4.68	26.92
6	H.J. Andrews	285	0.16	2.19	5.74	5.73	72.87	285	0.16	1.45	5.97	5.65	120.65	294	0.03	2.45	4.60	5.25	35.48
5	Alsea Forest	271	0.16	3.85	8.64	8.54	179.57	271	0.16	1.13	3.93	4.03	85.65	274	0.08	2.14	4.13	4.57	67.61
18	Headquarters	145	0.16	2.29	5.11	5.52	35.19	145	0.16	3.39	8.89	10.00	60.81	150	0.10	2.45	5.50	5.89	112.20
19	Glacier NP	257	0.16	3.64	7.27	9.68	61.52	257	0.16	4.52	9.06	11.29	78.71	260	0.03	2.82	4.10	6.24	8.32
24	Manitou	280	0.52	6.77	15.93	19.36	192.27	280	0.16	12.58	26.83	33.71	270.82	295	0.04	1.74	10.77	15.85	66.07
25	Alamosa	210	0.16	7.29	20.05	23.73	171.24	210	0.24	7.42	17.95	24.36	117.75	223	0.02	0.47	3.56	3.02	52.48
26	Bandelier NM	189	0.52	6.77	14.85	18.74	91.61	189	0.16	8.23	19.61	23.55	158.72	193	0.07	2.19	9.05	12.30	79.43
8	Yosemite NP	134	0.52	2.19	6.27	9.79	51.53	134	0.16	3.55	16.55	24.36	200.98	144	0.06	1.82	5.04	5.13	67.61
10	Sequoia NP	167	0.52	2.81	8.85	9.99	100.66	167	0.16	3.55	20.36	25.81	125.97	178	0.03	1.45	5.30	5.50	64.57
12	Tanbark Flat	130	0.52	4.58	26.17	21.97	359.14	130	0.24	9.03	66.11	60.97	917.47	135	0.12	3.89	33.19	23.99	645.65

Table IIIb. Minimum, 25th percentile, arithmetic mean, 75th percentile, and maximum weekly deposition statistics for sulfate, nitrate, and hydrogen ions (mg/m^2) during precipitation events. Site numbers refer to Figure 1.

		Sulfate						Nitrate						Hydrogen Ion					
Site		N	Min	25th	Mean	75th	Max	N	Min	25th	Mean	75th	Max	N	Min	25th	Mean	75th	Max
3	Hoh River	273	0.00	3.62	21.74	31.85	161.16	273	0.004	0.89	5.00	7.39	29.00	281	E-5	0.03	0.25	0.37	1.62
6	H.J. Andrews	285	0.16	3.50	13.24	17.09	72.46	285	0.004	2.06	6.01	8.92	28.03	294	7E-6	0.03	0.19	0.28	1.09
5	Alsea Forest	271	0.00	4.15	18.41	26.06	141.02	271	0.002	0.71	4.17	6.01	26.96	274	2E-5	0.02	0.14	0.21	1.02
18	Headquarters	143	0.003	2.32	6.73	9.32	26.98	143	0.004	2.01	6.95	11.05	24.46	148	2E-5	0.02	0.10	0.15	0.45
19	Glacier NP	257	0.002	3.11	5.10	11.05	48.01	257	0.001	2.70	6.18	8.61	33.78	260	4E-7	0.02	0.11	0.15	0.82
24	Manitou	280	0.05	2.21	11.91	16.84	65.34	280	0.00	3.01	13.26	19.28	78.87	295	2E-6	0.004	0.13	0.16	1.22
25	Alamosa	210	0.003	2.18	7.19	9.71	36.24	210	0.003	1.37	4.88	7.23	23.59	223	7E-7	0.001	0.02	0.02	0.38
26	Bandelier NM	189	0.19	3.02	11.21	15.76	62.16	189	0.002	2.14	9.53	14.34	45.55	193	1E-5	0.01	0.11	0.16	0.91
8	Yosemite NP	133	0.02	2.97	11.61	13.31	72.44	133	0.09	3.86	14.43	22.07	118.90	143	4E-6	0.01	0.15	0.20	1.03
10	Sequoia NP	166	0.58	3.54	14.05	17.53	203.87	166	0.11	5.55	17.01	18.56	161.64	177	2E-6	0.01	0.16	0.19	2.50
12	Tanbark Flat	130	0.09	5.38	19.68	31.43	92.41	130	0.002	9.29	28.49	40.81	106.59	135	1E-5	0.02	0.32	0.52	1.79

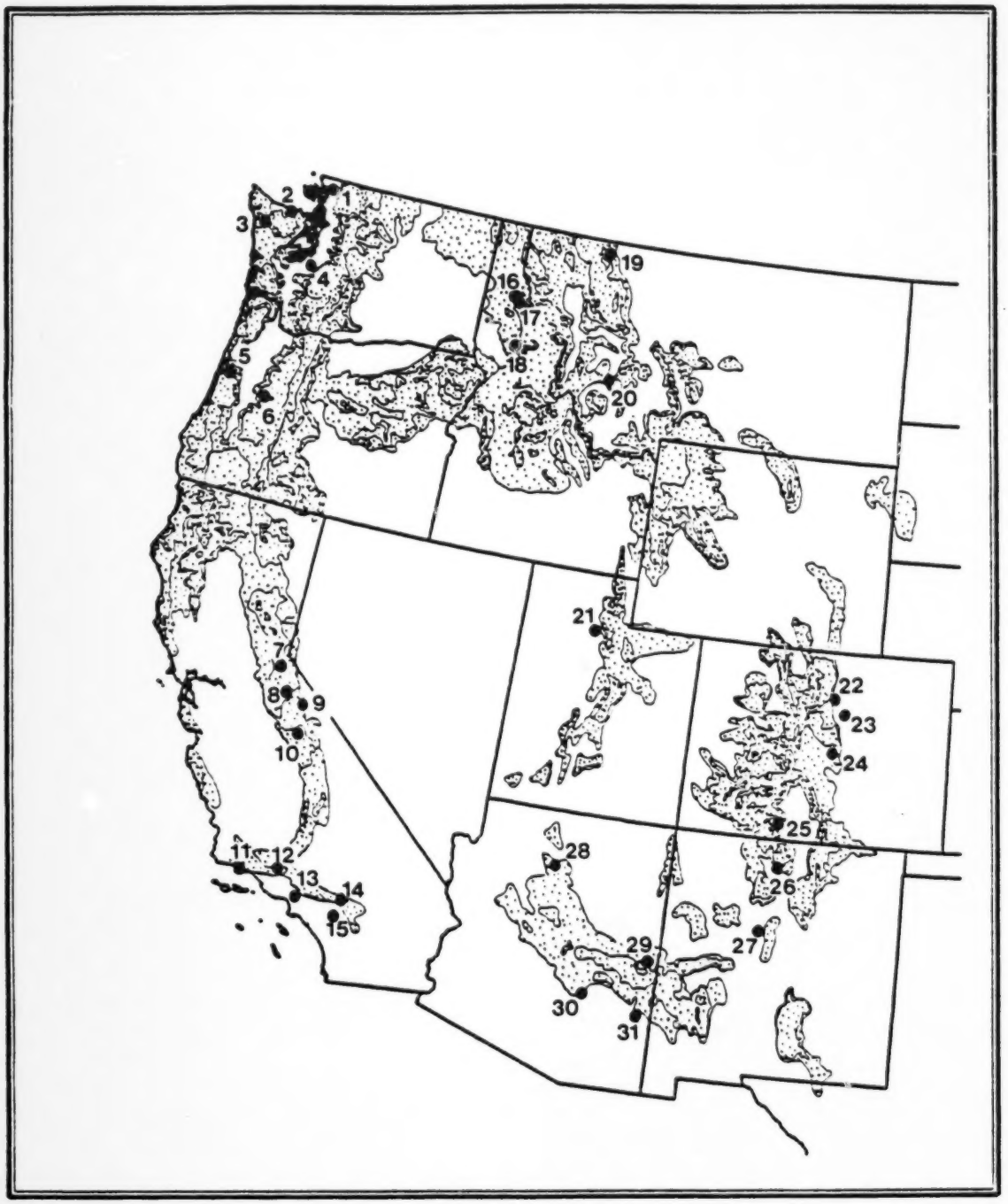

Figure 1. Locations of SO_2, O_3, and acid precipitation monitoring sites within 20 km of coniferous forest ecoregions (shaded).[31] The site information is presented in Table I.

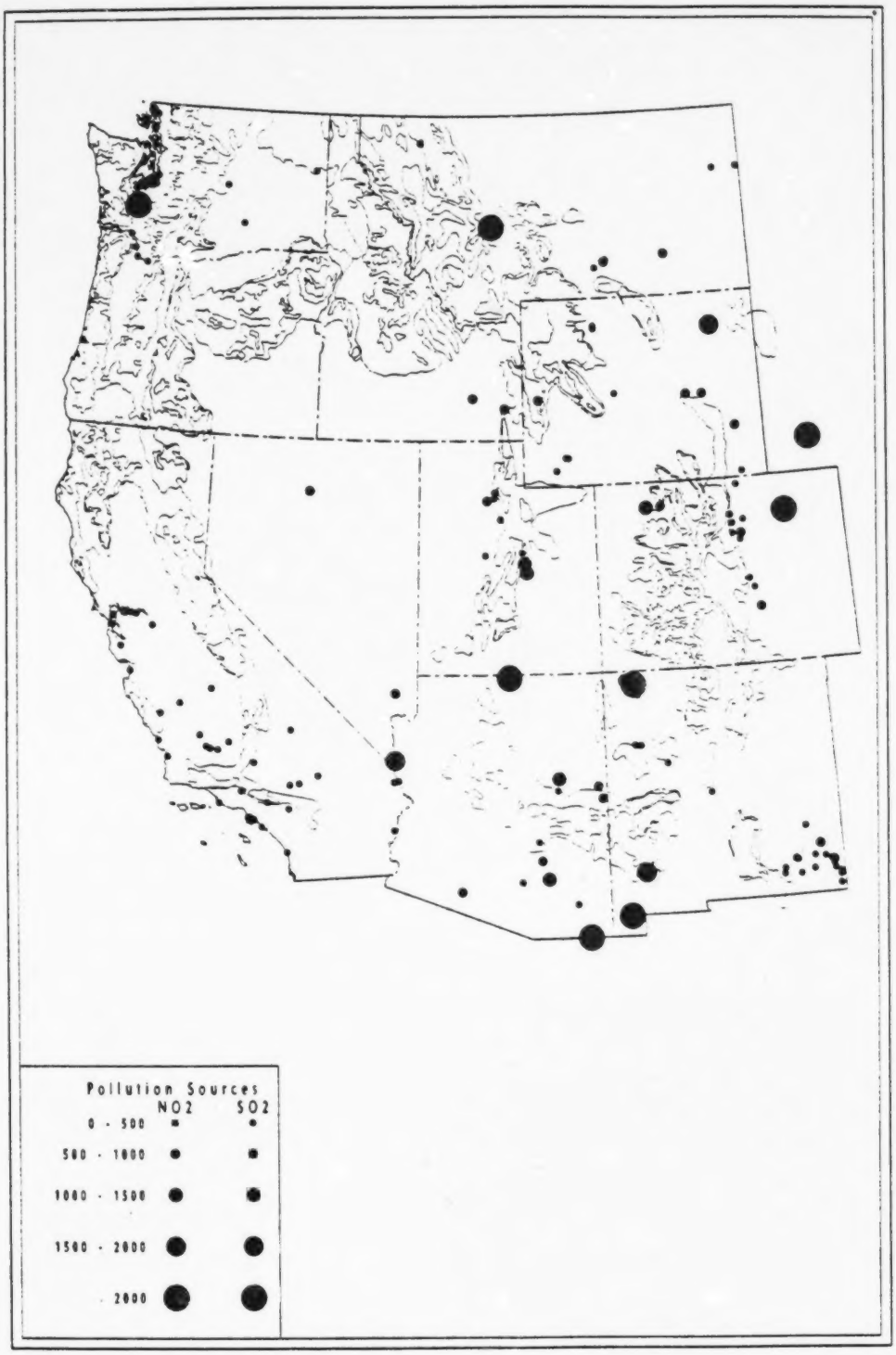

Figure 2. Point sources of SO_2 and NO_2 emitting more than 100 metric tons/year. Emission estimates are for 1985 (NEDS).

Figure 3. Spatial and temporal patterns in ambient [SO_2] using cumulative mean monthly fractiles expressed as percent of total observed hours. The shaded areas illustrate the percent of hours/month during which [SO_2] > 80 ppb, the middle zone relates to the percent of hours/month with 30 < [SO_2] < 80 ppb, and the remaining area represents the percent hours/month for which [SO_2] < 30 ppb. (For explanation of #s, see Table I).

Figure 4. Spatial and temporal patterns in ambient [O_3] using cumulative mean monthly fractiles expressed as percent of total observed hours. The shaded areas illustrate the percent of hours/month during which [O_3] > 100 ppb, the middle zone relates to the percent of hours/month with 60 < [O_3] < 100 ppb, and the remaining area represents the percent hours/month for which [O_3] < 60 ppb. (For explanation of #s, see Table I).

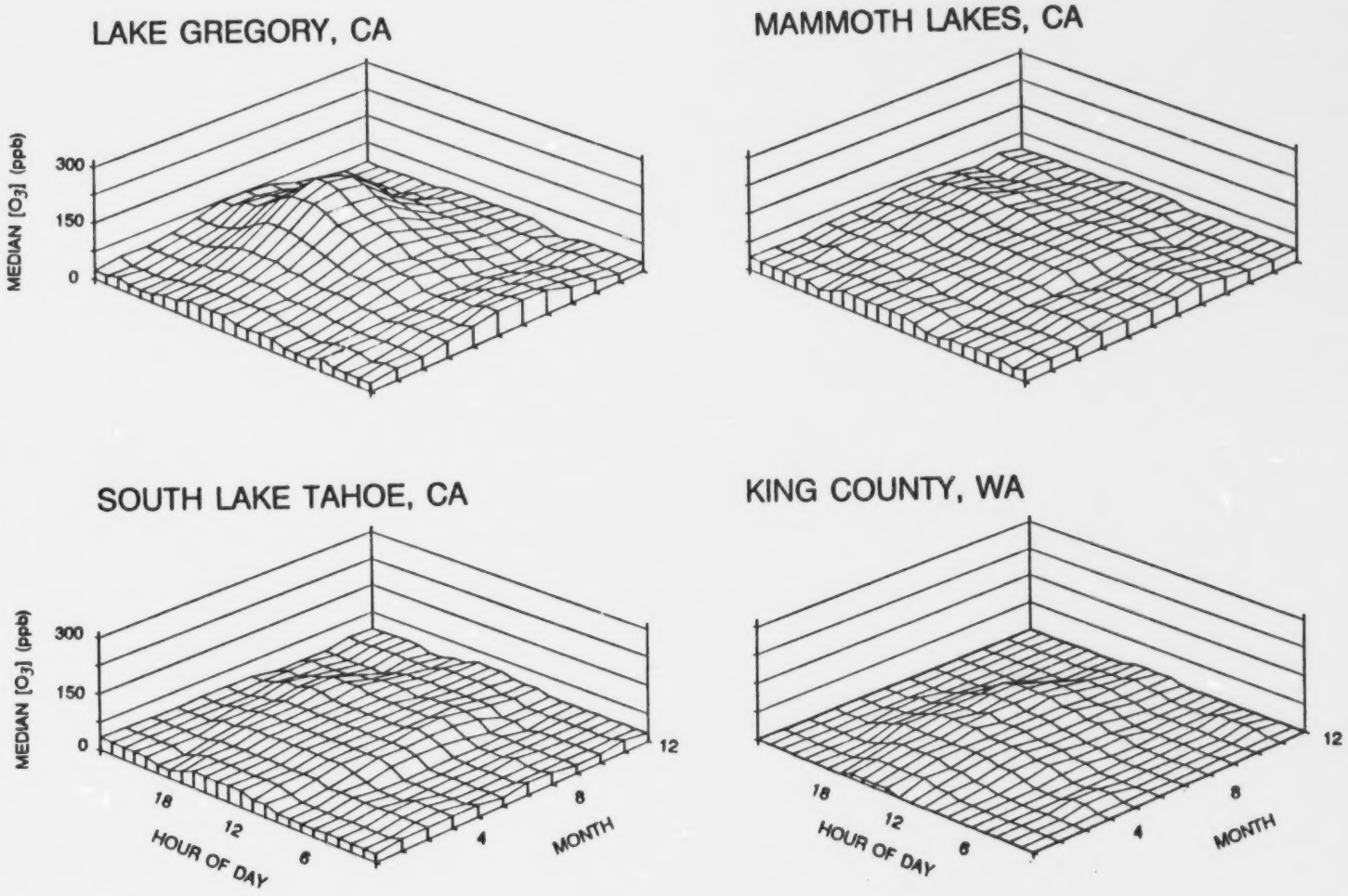

Figure 5. Median diurnal patterns in ambient [O_3] (ppb) by month for Lake Gregory, CA, Mammoth Lakes, CA, South Lake Tahoe, CA, and King County, WA.

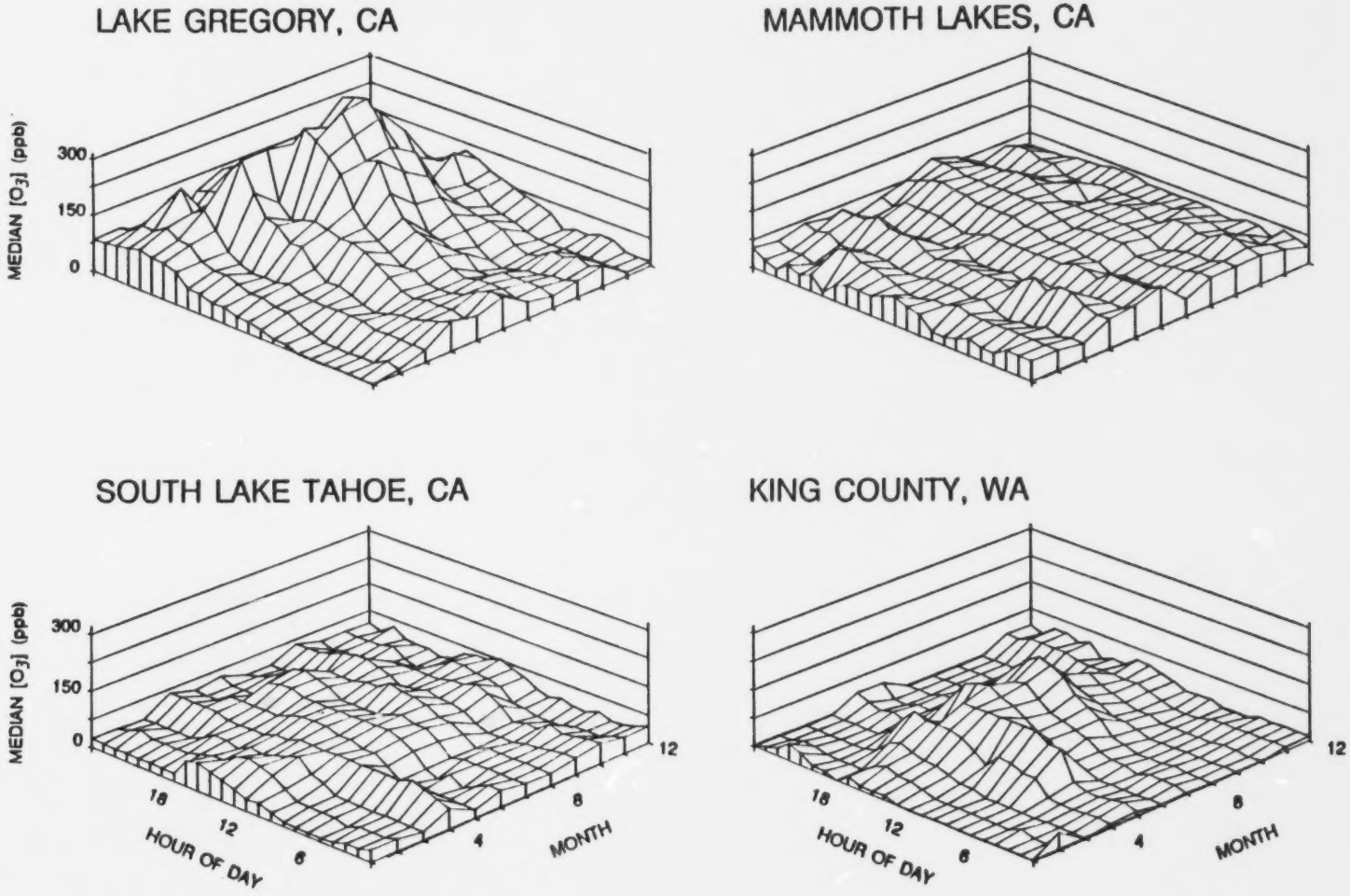

Figure 6. Diurnal patterns for the worst O_3 day (ppb) on record by month for Lake Gregory, CA, Mammoth Lakes, CA, South Lake Tahoe, CA, and King County, WA. Worst day is defined as that with the highest peak concentration.

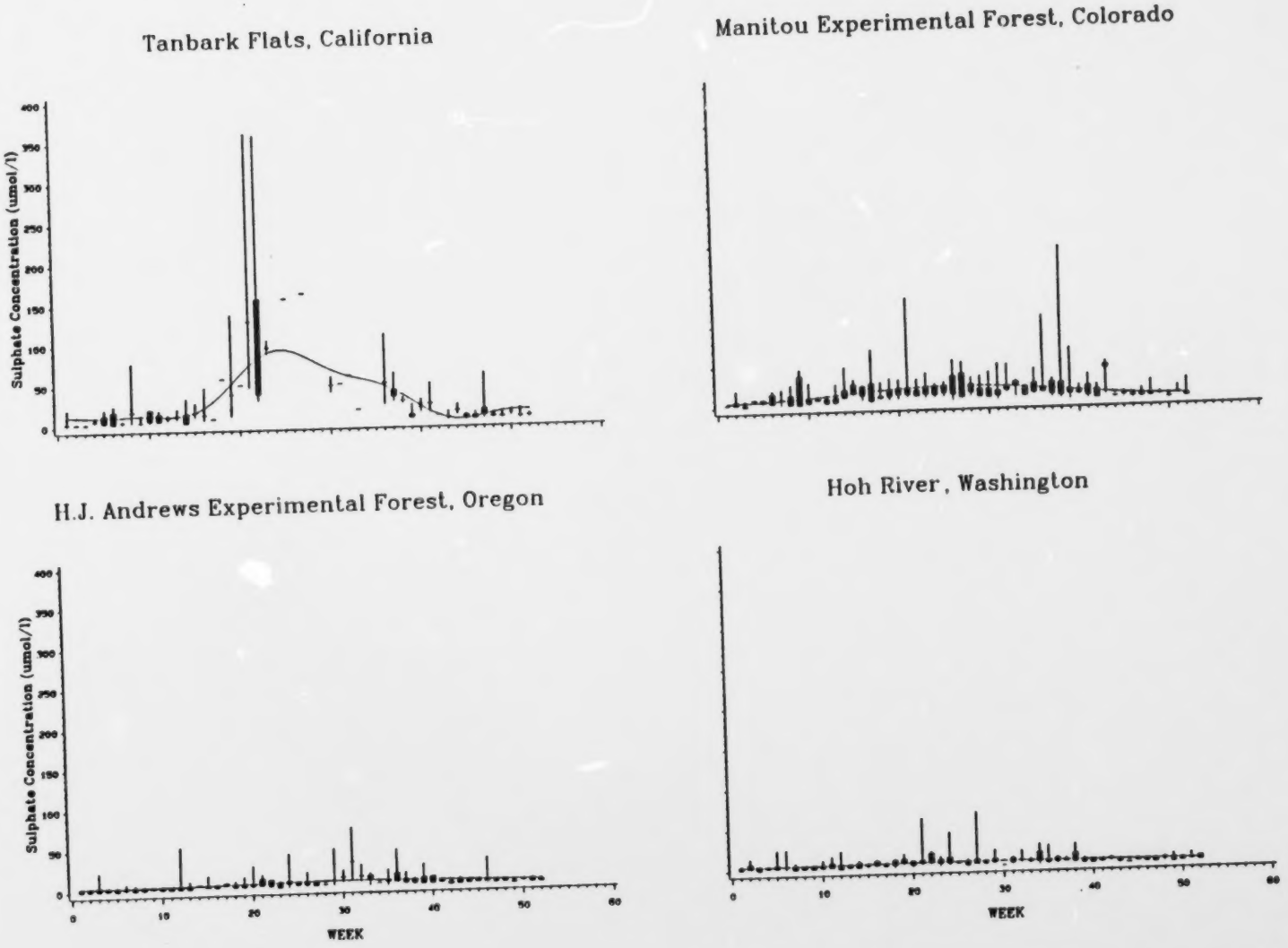

Figure 7. Seasonal patterns in sulfate concentrations in precipitation across the West as described by a Fourier series fitted to the data using least squares regression. The curve is superimposed on the weekly minimum, 25th percentile, 75th percentile, and maximum values for the period of record.